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A COMPUTER BASED PHYSIOLOGICAL TEMPERATURE MEASUREMENT SYSTEM

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ABSTRACT

A computer based, multichannel physiological temperature monitoring system is described. Thermistor probes are used as temperature transducers. A constant current thermistor driver converts the resistance of the thermistor probe to a temperature dependent voltage. This voltage is digitized by a multichannel analog to digital converter on command of a small computer. The computer controls the rate of data collection, stores the data, and performs the necessary algebraic manipulations to convert the data to a tabular or graphic temperature display. System operation, including thermistor calibration, data collection, and data reduction is discussed. Flow charts of representative software and schematics of hardware are included.

I. INTRODUCTION

A system for the acquisition, storage, manipulation, and display of temperature data in physiological experiments is described. The system was developed to measure regional cerebral temperature changes during early transient incapacitation following high doses of whole-body irradiation to subhuman primates.

Heat is a by-product of metabolic and functional activity in brain tissue. The rate of heat production and the rate of heat clearance can be related to changes in brain physiology.[1,4] In normal brain tissue there are two distinctly different types of temperature change related to brain function. First, there are small changes, typically $0.05^{\circ}C$ in magnitude, related to changes in regional activity. The time course of these changes tends to be short, lasting from a few seconds to several minutes.[4] The second class of temperature changes is related to circadian rhythms. These changes are large, 1°- $2^{\circ}C$, and of long duration, typically several hours. Brain temperature changes of long duration have been reported following whole-body irradiation in rabbits,[2] and since early transient incapacitation is a short duration phenomenon, it is reasonable to expect short duration changes in brain temperature to accompany it.

Any system for the measurement of brain temperature must then meet the following criteria. First, it must possess adequate resolution to detect fluctuations in temperature of $0.05^{\circ}C$ while possessing adequate dynamic range to detect changes of several degrees within the physiological temperature range of the animal. Second, it must possess adequate temporal resolution to detect fast changes while maintaining long-term stability to detect changes occurring over several hours.

II. SYSTEM DESCRIPTION

The system developed to meet these criteria uses thermistor probes for temperature sensing, thermistor drivers, an analog to digital converter, a digital computer, magnetic tape data storage, and graphic output via a high-speed line printer. The use of a digital computer provides multichannel capability; provides necessary resolution, dynamic range, and stability; and facilitates calibration, data manipulation, and display. A block diagram of this system is shown in Figure 1, and an example of the system's output is shown in Figure 2. Results of the experiments conducted at AFRRI on cerebral temperature following irradiation are published elsewhere.[3] The function of each major system component will now be examined in detail.

Thermistor probes. The thermistor probes used with this system to measure regional cerebral temperature are Fenwal Electronics Model GB32. These thermistors have a nominal resistance of 2 kilohms at 20°C.

Thermistor drivers. The thermistor driver module contains a reference voltage source, a constant current generator, and amplifiers. The reference voltage is derived from a standard mercury battery, is amplified, and is used to control the constant

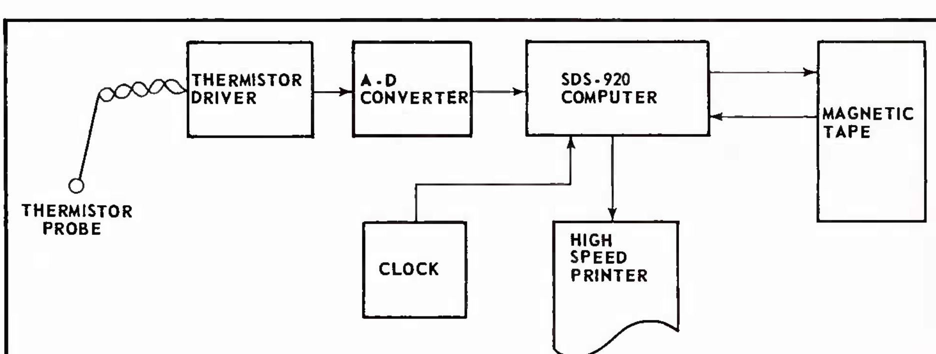

Figure 1. Block diagram of the system

current source. This source is an operational amplifier, and the thermistor probe is included in its feedback loop. A differential amplifier measures the voltage drop across the thermistor and provides a voltage gain of two. A final stage is utilized to provide an additional voltage gain of 20 (Figure 3).

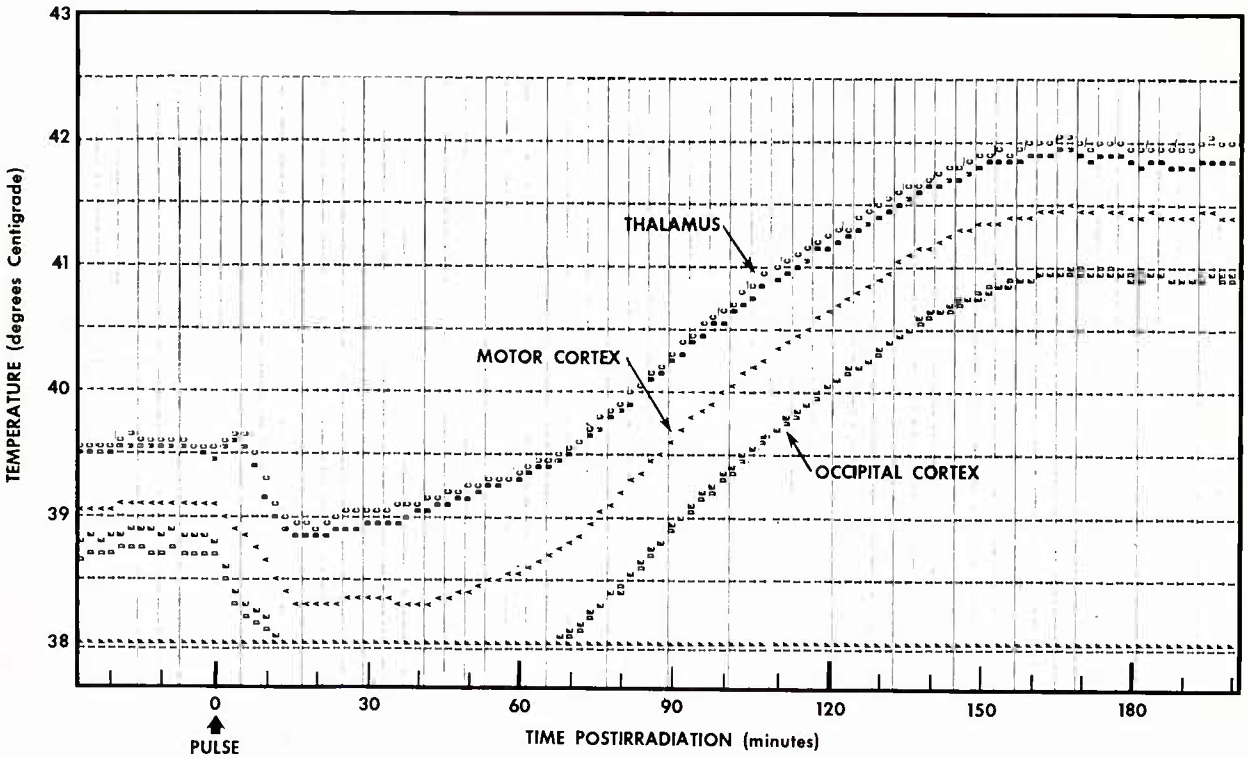

Figure 2. Example of temperature plot provided by the system as recorded by five thermistor probes (labeled A–E) in three regions of the brain of a rhesus monkey. Each point represents a 2-minute average of data taken once per second. Ionizing radiation was delivered to the animal in a pulse at time = 0.

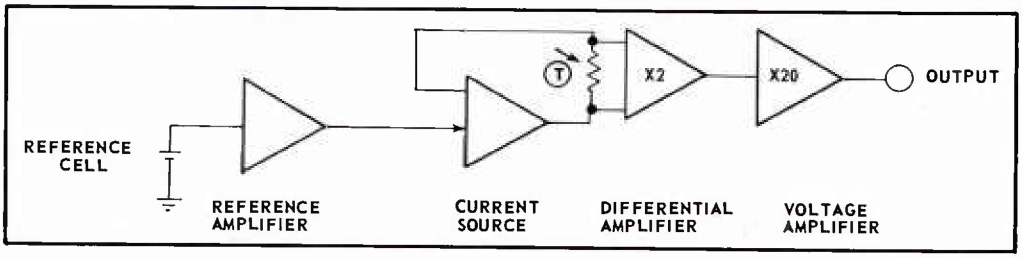

Figure 3. Block diagram of the thermistor drive electronics. T is the thermistor.

Heating due to current in the thermistor probe itself must be minimized to insure accurate temperature measurement. Currents in excess of 1 milliampere cause appreciable heating in the GB32 thermistor so a value of 100 microamperes was chosen as the thermistor drive current. The GB32 thermistor's resistance at 38°C is approximately 1000 ohms; therefore the voltage drop across the thermistor is approximately 0.1 volt. The AFRRI data acquisition system (DAS) analog to digital converter will accept signals between -8 and +8 volts dc. The overall voltage gain of the thermistor driver amplifiers is 40, yielding an 8-volt output at 20°C. The thermistor drive current and amplifier gain settings are thus optimized for the GB32 thermistor within the physiological temperature range.

Analog to digital (A-D) converter. The component that limits the accuracy of the system is the A-D converter. The converter utilized in the present system is capable of 12-bit resolution, and sign, from -8 to +8 volts, giving an accuracy of one part in 8000, or 2 mV in 16 volts. With the thermistor drive electronics connected to the input, the A-D converter becomes an ohmmeter capable of .5-ohm resolution. At a physiological temperature of 38°C, a .5-ohm change in a GB32 thermistor represents a change in temperature of approximately .015°C. This is the resolution limit of the system.

Computer system. The computer controls the data collection process, manipulates the data, and stores it on magnetic tape. In addition, the computer controls the calibration of new thermistors and displays results from experimental temperature determinations.

The computer in the current system is an SDS-920. Data are input via the A-D converter described above. The rate of data collection is controlled by an external

clock, input to the computer via its priority interrupt system. Output is to 7-channel, 200-bit per inch magnetic tape for data storage, and to a high-speed line printer for data display.

Software. Data collection and reduction programs are written in FORTRAN. Input of data from the thermistor probes via the A-D converter is accomplished by a FORTRAN callable machine language subroutine "ADCIN". ADCIN digitizes the input signals on all eight inputs of the A-D converter and stores the digital values in eight memory locations which may be accessed by a subscripted variable in the subroutine call statement. Once entered, ADCIN waits in an endless loop until it receives an interrupt, then digitizes and exits to the main FORTRAN program. Frequency of digitization is thus dependent on the frequency of a clock interrupt.

Three main FORTRAN programs utilize ADCIN. The first program is used to calibrate each channel of the resistance-measuring system of the A-D converter and the thermistor drivers. Each channel of the system is calibrated by connecting its input to a resistance box and collecting 60 data points at resistance settings between 500 and 1500 ohms in 100-ohm increments. A linear regression subroutine then provides an equation relating the integer output from the A-D converter to the actual resistance input to the thermistor driver for that channel. The program is capable of sequentially calibrating several channels and yields a paper tape output that contains the calibration equation and channel identification information.

Since thermistor probes are permanently implanted in animals and thus are used only once, a program was developed to calibrate large numbers of thermistors. A reference thermistor, connected to one channel of the system, is used as the

standard against which the other thermistors are calibrated; therefore, the accuracy of the system depends on the calibration of this reference thermistor. In the brain temperature study, an overall accuracy of $\pm 0.1^{\circ}C$ was adequate over the physiological temperature range of interest. Accordingly, a steel-clad Yellow Springs Instrument Company telethermometer probe was calibrated in a water bath against a laboratory thermometer of $0.1^{\circ}C$ accuracy. Temperature and probe resistances as measured with a standardized digital ohmmeter were recorded over a temperature range of 20°-$50^{\circ}C$. A least squares regression analysis was used to fit a calibration equation to the data.

In the thermistor calibration program, the reference thermistor is connected to one channel of the system, while another channel is connected to the thermistor to be calibrated. Up to 12 thermistor probes may be calibrated by switching between them sequentially during the calibration procedure. The reference and probe thermistors are then immersed in a water bath, and data are collected at temperatures from 35° to $45^{\circ}C$ in $0.5^{\circ}C$ increments, using ADCIN. At each point, the reference thermistor is the independent variable while the output of the unknown thermistor is the dependent variable. The channel calibration paper tape is read into the system and is used to allow the computer to calculate the resistance of both the reference and probe thermistors. Using the calibration constants for the reference thermistor, the temperature of the water bath is calculated. After the resistance of the thermistor probe and the bath temperature at each calibration point have been determined, a linear regression analysis is performed to yield a calibration equation for each thermistor probe of the following form:

$$\text{Ln } R = mT + b$$

where R = thermistor resistance,

T = temperature of bath,

and m and b are constants unique to each thermistor.

This calibration information is then output on paper tape along with probe identification information for later input during the data reduction phase.

The data collection program simply collects data from all eight channels of the A-D converter, via ADCIN, and outputs the average of each 10 samples along with a time code expressed in seconds of the day on digital magnetic tape in binary format. Since temperature in most physiological applications does not change rapidly, the sampling rate is once per second.

Prior to each thermistor calibration run and each data collection run, the channel calibration program must be used to eliminate errors due to drift in the A-D converter and the thermistor drive electronics. The thermistor probes need to be calibrated only once since their characteristics are stable with time.

The final program reduces the data from the data collection program. This program accepts a resistance calibration tape, a thermistor calibration tape, and a punched card assigning each thermistor to an input channel. The computer reads the magnetic tape generated by the data collection program, calculates the temperature measured by each channel and, at the discretion of the operator, plots the average of from 1 to n 10-second data points on the line printer. A good working plot is obtained by averaging 2 minutes of data ($n = 12$), as illustrated in Figure 2. Thermistor

driver schematics and circuit descriptions, together with flow charts of all software, are included in the appendixes.

III. DISCUSSION

This system has been used successfully to investigate the effects of radiation on cortical and deep brain temperatures in the monkey. Its accuracy is largely dependent on the care taken in calibrating both the reference thermistor and the individual thermistor probes. Experience has shown that the precision of the system approaches the theoretical resolution limit of $.015^{\circ}C$ when the data are averaged by the present data collection program. Absolute accuracy, however, is no better than the calibration accuracy of the reference thermistor. In the present brain temperature application, accuracy of $\pm 0.1^{\circ}C$ is considered adequate.

The primary advantage of this system is that the data are available in a format that may be easily manipulated by the computer. Temperature differentials are easily plotted, and correlation analysis of temperature with other physiological parameters is facilitated.

The primary disadvantage relative to the present system is that the data acquisition program requires considerable computer time since the SDS-920 is not capable of time-sharing operation. If the system were adapted to run with a time-sharing computer, more extensive use of this temperature monitoring system would be practical.

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APPENDIX A

Thermistor Driver Schematics and Circuit Descriptions

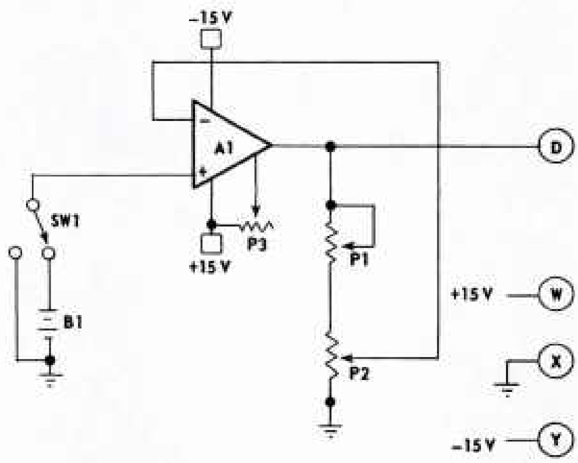

Figure A-1. Schematic diagram of voltage reference module

Table A-I. Parts List for Voltage Reference Module

A1	Analog Devices model 118-K operational amplifier
B1	1.35 V mercury battery Mallory RM-42R
P1	100 ohm trimpot
P2	10 kilohm trimpot
P3	50 kilohm trimpot
SW1	SPDT miniature switch

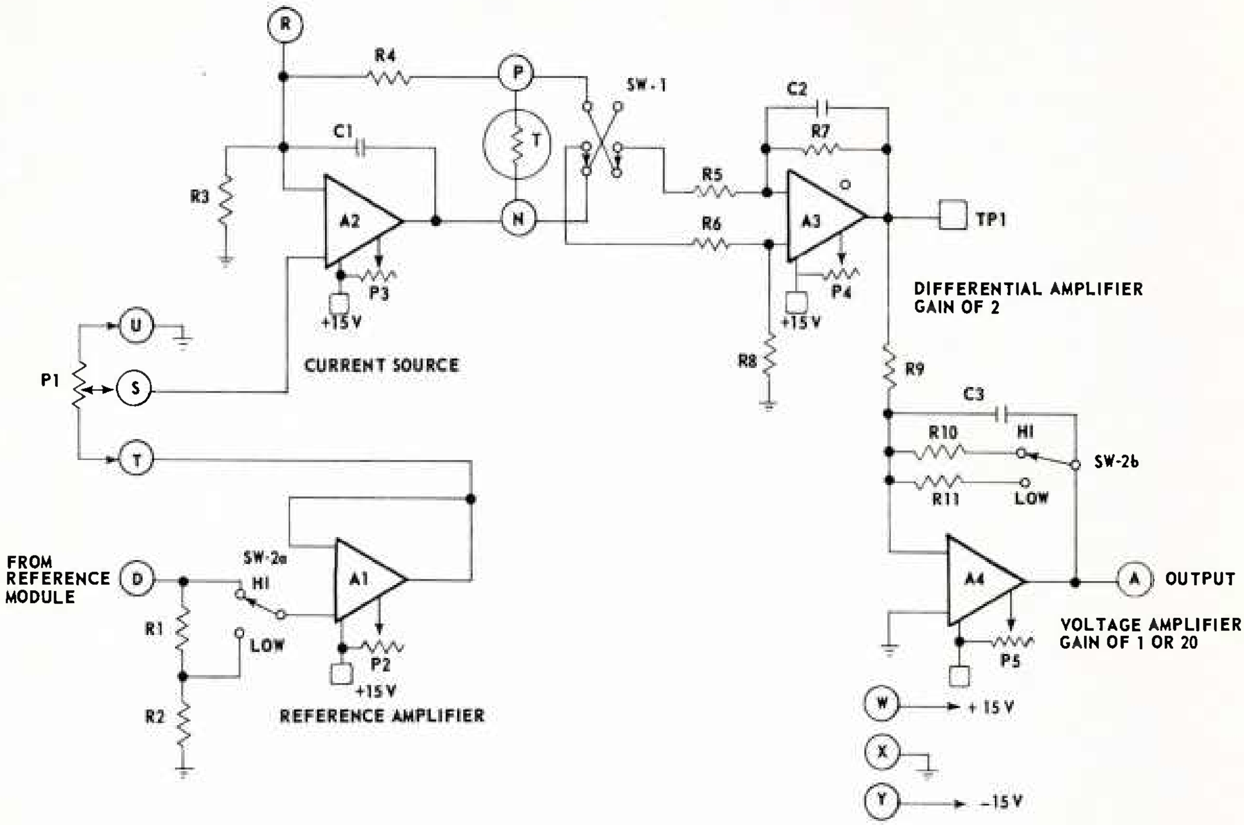

Figure A-2. Schematic diagram of thermistor drive and data amplifier module

Table A-II. Parts List for Thermistor Drive and Data Amplifier Module

A1, A2, A4	Analog Devices model 118-K operational amplifiers	R2	500 ohm 1% film resistor, ½ watt
A3	Analog Devices model 40-K FET operational amplifier	R3	2000 ohm 1% film resistor, ½ watt
C1, C3	.1 microfarad 100 Volt Mylar capacitor	R4	100 ohm 1% film resistor, ½ watt
C2	.068 microfarad 100 Volt Mylar capacitor	R5, R6	1 megohm 1% film resistor, ½ watt
P1	1000 ohm 10-turn potentiometer, Amphenol 4101B	R7, R8	2 megohm 1% film resistor, ½ watt
P2, P3, P5	50 kilohm trimpot	R11	200 kilohm 1% film resistor, ½ watt
P4	1000 ohm trimpot	SW-1, SW-2	DPDT miniature switch JBT-type JMT 223 or equivalent
R1, R9, R10	10 kilohm 1% film resistor, ½ watt	T	Thermistor approx 2K at 20° C for physiological data acquisition

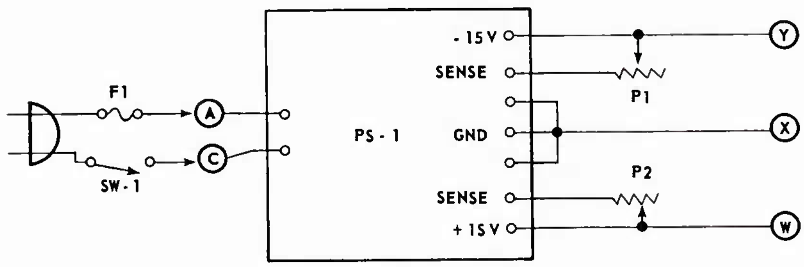

Figure A-3. Schematic diagram of power supply module

Table A-III. Parts List for Power Supply Module

F1	½ ampere slo-blow fuse
P1, P2	10 kilohm trimpots
PS-1	Analog Devices model MDP-15/300 power supply module
SW-1	SPDT miniature switch JBT type JMT-123 or equivalent

APPENDIX B

Systems Software Flow Charts

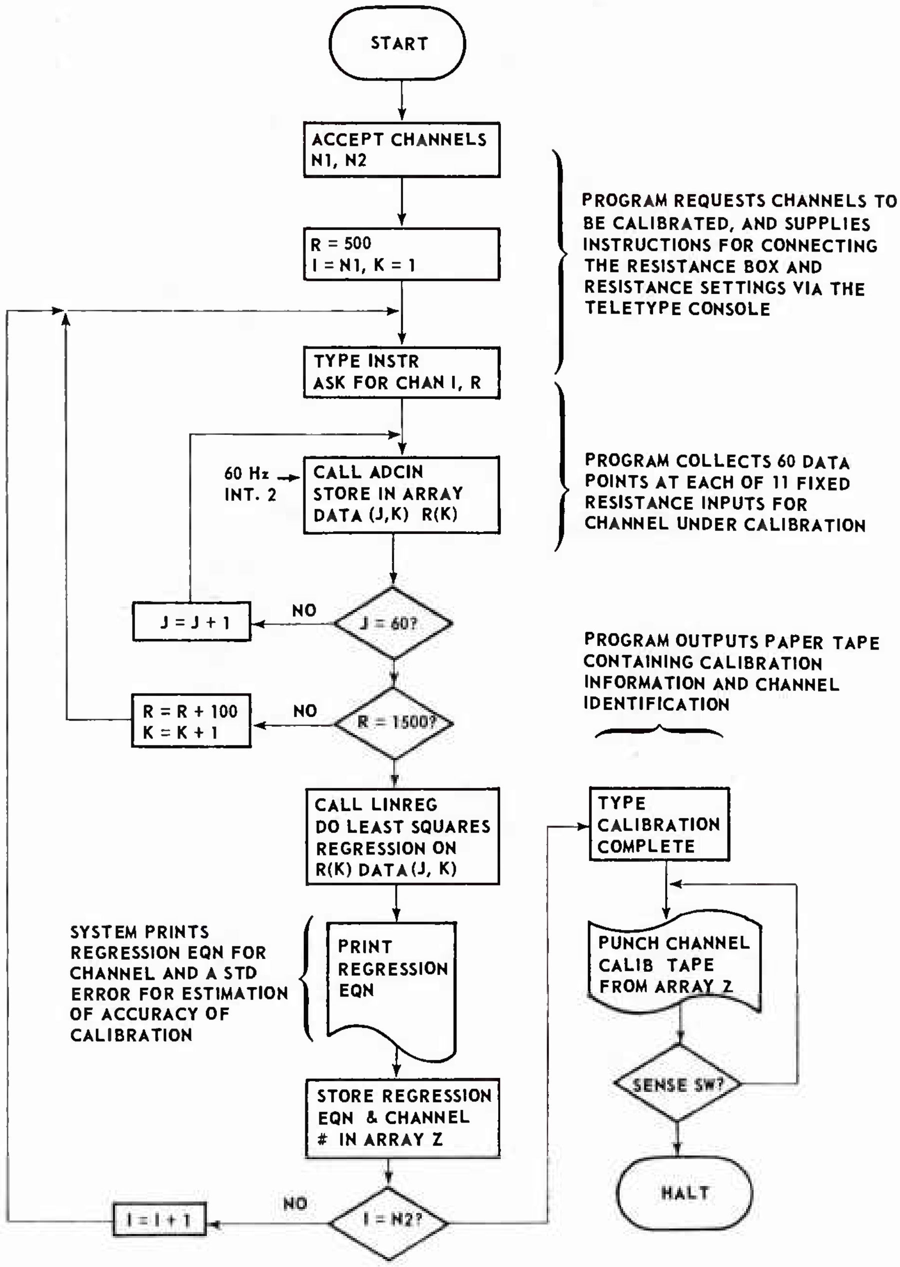

Figure B-1. Channel calibration program flow chart

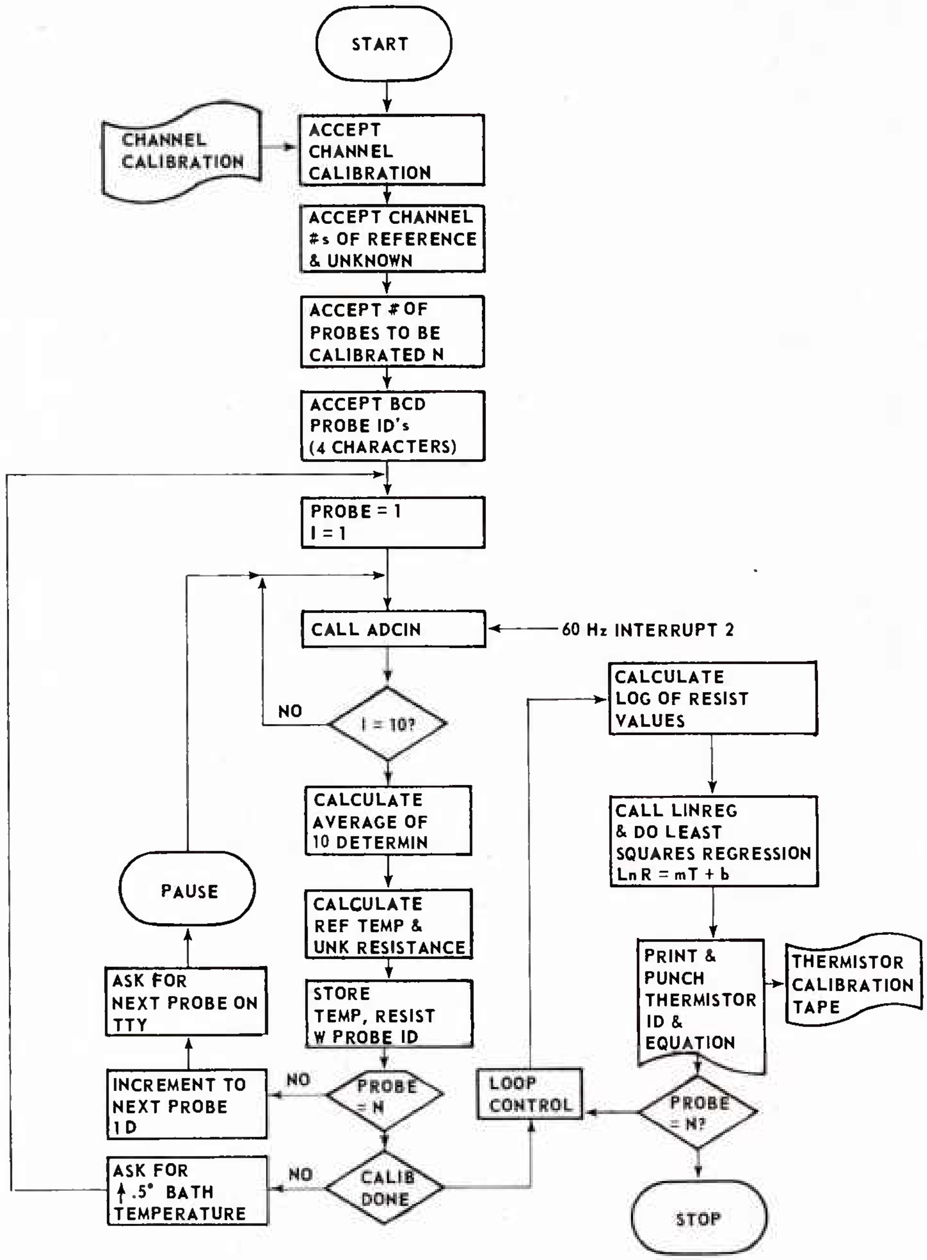

Figure B-2. Thermistor calibration program flow chart

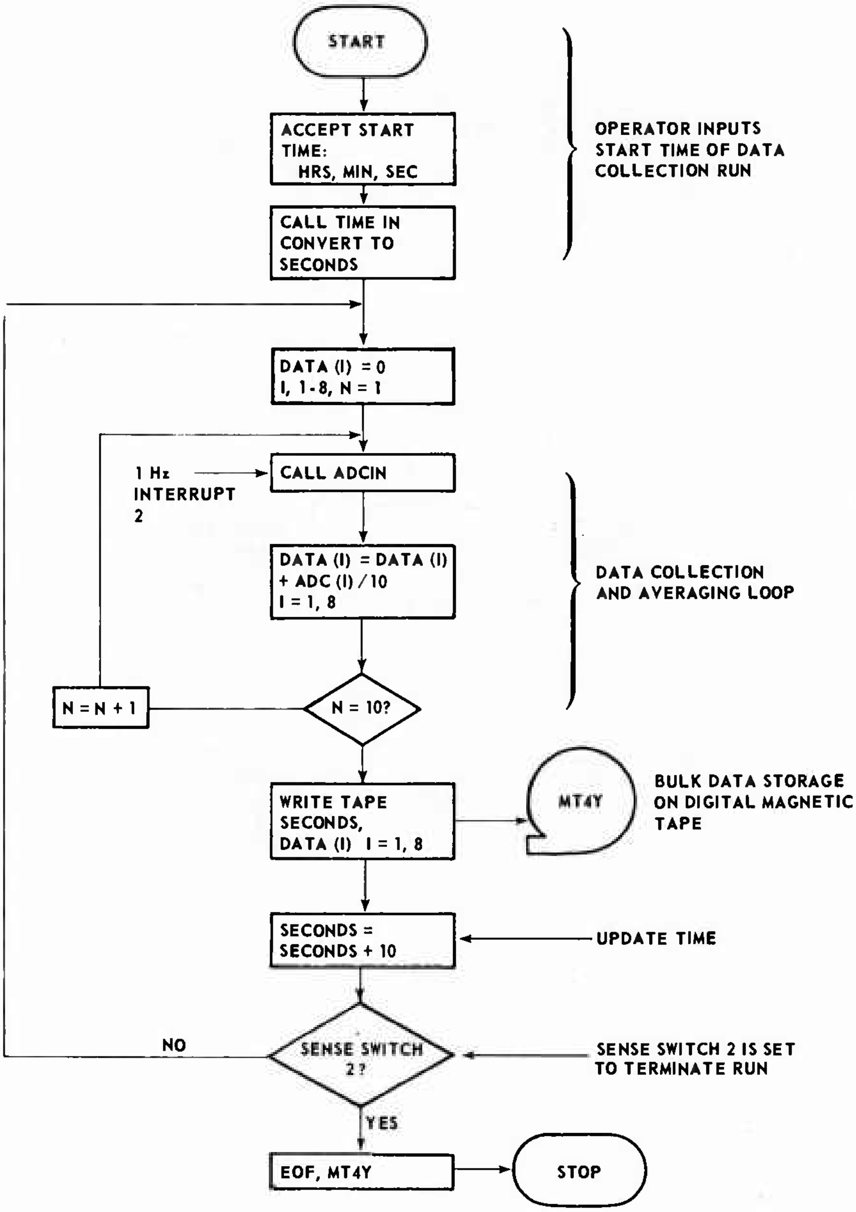

Figure B-3. Data collection program flow chart

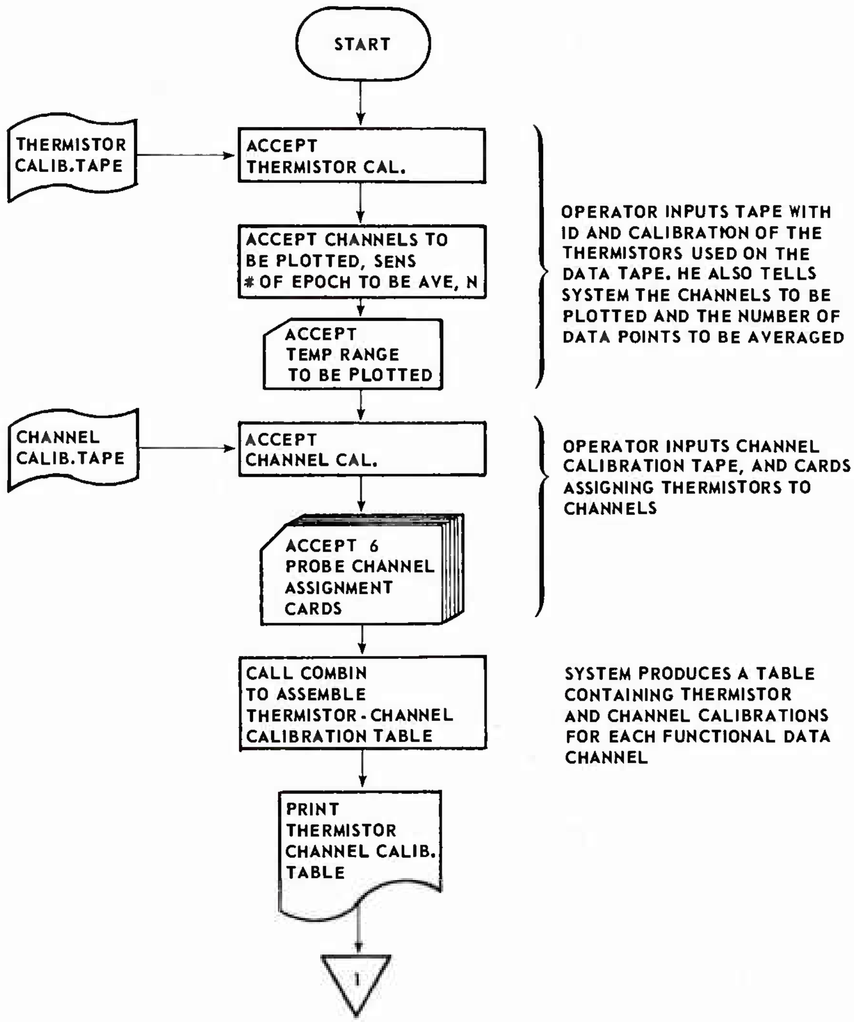

Figure B-4. Temperature data reduction and plotting program flow chart

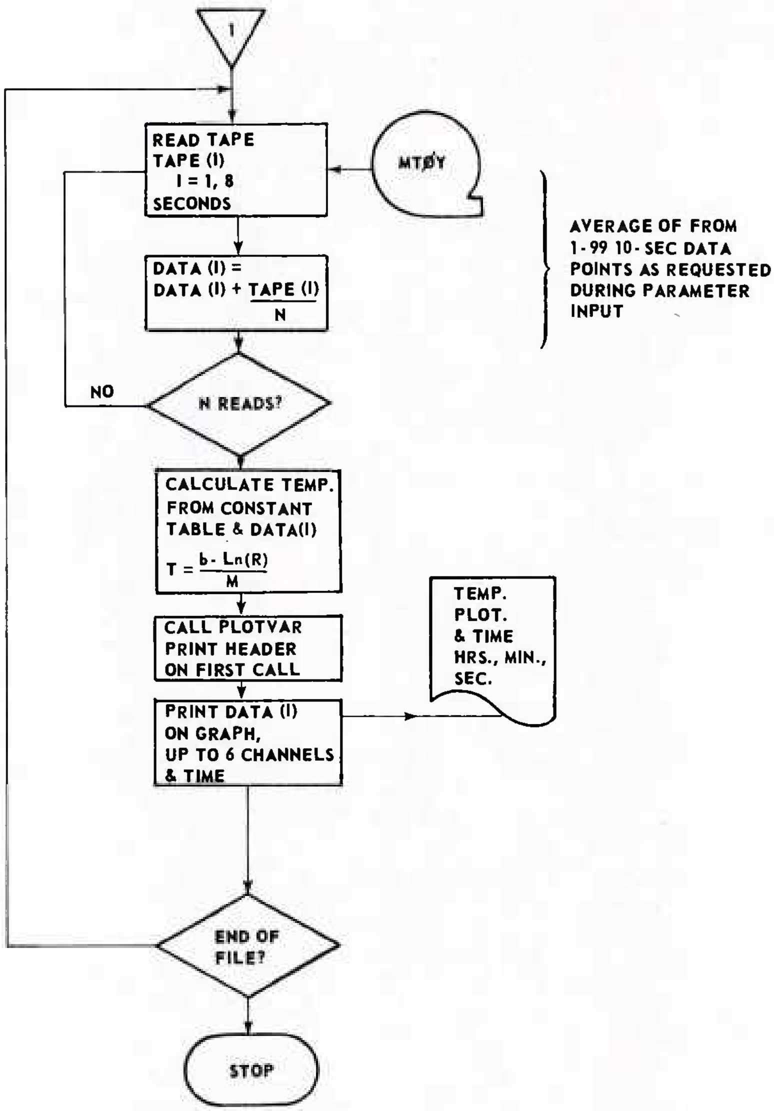

Figure B-4 (continued)

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13. ABSTRACT

A computer based, multichannel physiological temperature monitoring system is described. Thermistor probes are used as temperature transducers. A constant current thermistor driver converts the resistance of the thermistor probe to a temperature dependent voltage. This voltage is digitized by a multichannel analog to digital converter on command of a small computer. The computer controls the rate of data collection, stores the data, and performs the necessary algebraic manipulations to convert the data to a tabular or graphic temperature display. System operation, including thermistor calibration, data collection, and data reduction is discussed. Flow charts of representative software and schematics of hardware are included.